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## Energy Efficiency and IAQ

# Simultaneous Improvements In Relocatable Classrooms

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**W**e designed and constructed four energy-efficient relocatable classrooms (RCs) to demonstrate technologies with the potential to simultaneously improve energy efficiency and indoor environmental quality (IEQ).

Each RC was equipped with two HVAC systems: a standard 10 SEER heat-pump air-conditioning system (HPAC), and an energy-efficient indirect/direct evaporative cooler (IDEC), which is suitable for use where outdoor summertime humidities are moderate to low.

IEQ monitoring results indicate that important concentration reductions of indoor CO<sub>2</sub> (implying ventilation increases) and VOCs (implying potential reduction in health risks) were achieved while average cooling and heating energy costs were simultaneously reduced by about one-half, and one-third, respectively.

### Field Study

We placed two high-performance RCs each at a San Francisco Bay Area elementary school (SDA) and a Modesto elementary school (SDB). We refer to classrooms of type "A" and "B" located in SDA and SDB as SDA-A, SDA-B, SDB-A, and SDB-B.

Field study phases included RC design specification and construction, RC installation at schools and instrumentation; field measurement and data collection during cooling and heating seasons, and data analysis. More detail on research methods is provided by Shendell.<sup>1</sup>

The high performance RC design used in this study combines available energy efficient construction materials and methods including additional wall, floor, and ceiling insulation; ceiling vapor barrier; "cool roof" reflective roof coating, low-emissivity window glazing; and efficient (T8) fluorescent lighting.<sup>2</sup>

The IDEC supplies continuous ventilation at  $\geq 15$  cfm (7.5 L/s) per person, even when heating or cooling is not required. Additionally, compared to the standard heat-pump system, it

consumes about 70% less cooling energy. As it has no compressor and a quiet fan, the noise output from the system is lower. Incorporated into the IDEC is an 85% efficient (annual fuel utilization efficiency) gas-fired hydronic space heating system and an inlet filter system with 65% ASHRAE dust spot efficiency.<sup>3</sup>

Both the IDEC and the HPAC system controls, as currently designed, require that the system be turned on to provide the required ventilation. In the case of the heat pump system, this action is tied to the temperature setpoint, such that outside air is only supplied when heating or cooling is needed. The IDEC system supplied room air through three 2 ft<sup>2</sup> (0.2 m<sup>2</sup>) ceiling diffusers evenly spaced across the length of the RC, while the HPAC systems used two.

To study VOC source reduction potential, SDA-A and SDB-A received alternative low-VOC emitting wall panels, carpet, and ceiling panels.<sup>4</sup> Target VOCs were selected based upon those defined as toxic air contaminants by the state of California and odorous compounds.<sup>5</sup> RCs SDA-B and SDB-B were constructed using the manufacturer's standard materials. Otherwise, all four RCs were constructed identically. One exception was that "Nylon-6,6" broadloom carpet was installed in SDA-B while SDB-B received "Nylon-6" broadloom carpet, resulting in slightly different VOC emissions profiles.

### Results

The patterns of operation of HVAC systems by the teachers directly influenced classroom IEQ parameters during the school day. The current design requires both systems to be turned on to provide the required ventilation. The heat pump thermostat provides a "fan-only" setting, but the teachers may prefer not to use it. The IDEC control requirement is simply to be "on" during occupancy because the fan provides continuous 100% outside air when operational.

### About the Authors

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# Technical Feature

Cooling Season	10 SEER HPAC			IDEC		
	Mean $\pm$ Std.	Max.	95%	Mean $\pm$ Std.	Max.	95%
Indoor Temp.	72 $\pm$ 3.9°F	82°F	78°F	71 $\pm$ 3.8°F	80°F	76°F
Outdoor Temp.	82 $\pm$ 8.7°F	104°F	98°F	77 $\pm$ 8.0°F	104°F	88°F
Indoor CO <sub>2</sub>	960 $\pm$ 480 ppm	2,770 ppm	1950 ppm	830 $\pm$ 530 ppm	2,880 ppm	2,163 ppm
HCHO <sup>a</sup>	21 $\pm$ 5 ppb	28 ppb	28 ppb	8.0 $\pm$ 2.8 ppb	19 ppb	19 ppb
PM <sup>b</sup> (0.3 – 5 $\mu$ m)	240 $\pm$ 260 $\mu$ g m <sup>-3</sup>	1,500 $\mu$ g m <sup>-3</sup>	830	360 $\pm$ 380 $\mu$ g m <sup>-3</sup>	3,000 $\mu$ g m <sup>-3</sup>	1,100 $\mu$ g m <sup>-3</sup>
PM (0.3 – 1 $\mu$ m)	20 $\pm$ 17 $\mu$ g m <sup>-3</sup>	140 $\mu$ g m <sup>-3</sup>	51 $\mu$ g m <sup>-3</sup>	28 $\pm$ 35 $\mu$ g m <sup>-3</sup>	270 $\mu$ g m <sup>-3</sup>	76 $\mu$ g m <sup>-3</sup>
PM (0.3 $\mu$ m)	5.0 $\pm$ 3.4 $\mu$ g m <sup>-3</sup>	17 $\mu$ g m <sup>-3</sup>	11 $\mu$ g m <sup>-3</sup>	6.6 $\pm$ 6.1 $\mu$ g m <sup>-3</sup>	49 $\mu$ g m <sup>-3</sup>	18 $\mu$ g m <sup>-3</sup>
Indoor Sound	55.7 $\pm$ 9.7 dBA	84.2 dBA	69.1 dBA	55.9 $\pm$ 10.5 dBA	90.8 dBA	70.8 dBA
Energy Cost <sup>c</sup> /Day	\$0.96 $\pm$ 0.39	\$1.65	\$1.65	\$0.40 $\pm$ 0.27	\$1.23	\$0.88
Heating Season	10 SEER HPAC			IDEC		
	Mean $\pm$ Std.	Max.	95%	Mean $\pm$ Std.	Max.	95%
Indoor Temp.	70 $\pm$ 5.4°F	88°F	80°F	71 $\pm$ 5.1°F	92°F	82°F
Outdoor Temp.	59 $\pm$ 9.5°F	86°F	76°F	59 $\pm$ 7.5°F	88°F	73°F
Indoor CO <sub>2</sub>	1,370 $\pm$ 630 ppm	3,140 ppm	2,379 ppm	760 $\pm$ 370 ppm	2,600 ppm	1,527 ppm
HCHO <sup>a</sup>	14 $\pm$ 9 ppb	34 ppb	34 ppb	4.5 $\pm$ 1.3 ppb	8.5 ppb	8.5 ppb
PM (0.3 – 5 $\mu$ m)	74 $\pm$ 72 $\mu$ g m <sup>-3</sup>	580 $\mu$ g m <sup>-3</sup>	210 $\mu$ g m <sup>-3</sup>	48 $\pm$ 49 $\mu$ g m <sup>-3</sup>	640 $\mu$ g m <sup>-3</sup>	130 $\mu$ g m <sup>-3</sup>
PM (0.3 – 1 $\mu$ m)	11 $\pm$ 7.7 $\mu$ g m <sup>-3</sup>	48 $\mu$ g m <sup>-3</sup>	26 $\mu$ g m <sup>-3</sup>	8.3 $\pm$ 6.4 $\mu$ g m <sup>-3</sup>	130 $\mu$ g m <sup>-3</sup>	19 $\mu$ g m <sup>-3</sup>
PM (0.3 $\mu$ m)	3.8 $\pm$ 3.2 $\mu$ g m <sup>-3</sup>	16 $\mu$ g m <sup>-3</sup>	10 $\mu$ g m <sup>-3</sup>	3.2 $\pm$ 2.8 $\mu$ g m <sup>-3</sup>	15 $\mu$ g m <sup>-3</sup>	8.0 $\mu$ g m <sup>-3</sup>
Indoor Sound	55.5 $\pm$ 9.6 dBA	78.0 dBA	68.3 dBA	55.9 $\pm$ 10.5 dBA	86.8 dBA	70.7 dBA
Energy Cost <sup>c</sup> /Day	\$1.54 $\pm$ 0.79	\$3.60	\$2.90	\$1.03 $\pm$ 0.61	\$3.53	\$2.12

a Indoor-outdoor formaldehyde concentration.

b PM=Particulate matter in given instrument bin sizes, mass concentration calculated from particle count concentration, based upon bin size diameter and assumed density of 2 g cc<sup>-1</sup>. Outdoor PM concentrations (0.3 – 5  $\mu$ m) were 130 $\pm$ 140  $\mu$ g m<sup>-3</sup> and 30 $\pm$ 40  $\mu$ g m<sup>-3</sup> in the cooling and heating seasons, respectively.

c Assuming an electricity cost of \$0.14 kWh<sup>-1</sup> and natural gas cost of \$0.60 therm<sup>-1</sup> for equipment.

**Table 1: Summary schoolday statistics averaged across four occupied high performance relocatable classrooms monitored during 9 to 10 weeks in each of the cooling and heating seasons in Northern California during the 2001 – 2002 school year.**

## Temperature and CO<sub>2</sub>

Table 1 presents summarized data from the RCs. The temperatures in the classrooms were similar during the HPAC and IDEC weeks throughout the cooling and heating seasons, indicating that the systems are comparable at maintaining thermal conditions.

We observed teacher operation of the HVAC systems was not solely based upon thermal demand. In addition, they did not always turn the IDEC on in the morning as instructed. During periods when the teachers did not turn on the HVAC system, CO<sub>2</sub> concentrations were observed to rise above 1,000 ppm, with peaks reaching almost 3,000 ppm, irrespective of the HVAC system. During periods of window-only use, indoor CO<sub>2</sub> levels often exceeded 1,000 ppm, indicating that windows alone may not have provided adequate ventilation. Teachers' behavior was similar in the heating season, but the morning heating demands led to more consistent use of the IDEC. Mean heating season indoor CO<sub>2</sub> concentrations were 1370 $\pm$ 630 ppm and 760 $\pm$ 370 ppm for HPAC and IDEC weeks, respectively. The substantially lower CO<sub>2</sub> concentrations during IDEC operation weeks demonstrate the

benefits of continuous, adequate ventilation. During the cooling season, average schoolday indoor CO<sub>2</sub> concentrations across study RCs were 960 $\pm$ 480 ppm (average $\pm$ standard deviation) and 830 $\pm$ 530 ppm for HPAC and IDEC weeks, respectively.

## Indoor Pollution

The IDEC system's continuous ventilation effectively controlled concentrations of indoor-generated pollutants, as demonstrated by the formaldehyde data. Formaldehyde concentrations during the schoolday in both the cooling and heating seasons were higher during HPAC weeks than during IDEC weeks. Cooling season means were 21 $\pm$ 5 ppb and 8 $\pm$ 3 ppb, respectively, for HPAC and IDEC weeks. Heating season means were 14 $\pm$ 9 ppb and 4.5 $\pm$ 1.3 ppb, respectively. Lower formaldehyde concentrations during the heating season likely were the result of source material aging.

Indoor particulate matter (PM) concentrations generally were higher than outdoors, indicating that the occupant activities were a particle source. During the cooling season with frequent door and window use, there was increased infiltra-

# Technical Feature

tion of PM from outdoors. Average indoor PM concentrations were lower during HPAC operation across the size distribution, but they occasionally reached very high levels in both HVAC modes. During cooling weeks, the HPAC's recirculation of air through a low-efficiency filter may have been more effective than the 65% efficient single-pass filtration of the IDEC. During the heating season, the IDEC operation weeks had about 33% lower mean indoor PM concentrations, but higher maximum levels. Overall, the indoor PM concentrations were much lower during the heating season.

Figure 1 depicts average indoor-outdoor VOC and formaldehyde concentrations during IDEC operation in the cooling season (formaldehyde concentrations were divided by 10 for scaling). In SDA-A, constructed with selected alternative materials, these VOCs were at consistently lower concentrations than in classroom SDA-B, built with standard materials. In the other school district, the pattern is not as clear. The source of the elevated formaldehyde and acetaldehyde levels in classroom SDB-A may have been teaching and art materials. The elevated formaldehyde levels in that RC were transient, and dropped after a few weeks. The season average caprolactam concentration was 4.8 ppb in classroom SDB-B, the only RC where Nylon-6 broadloom carpet was installed. Low to non-detectable caprolactam concentrations occurred in the other classrooms.

The measured concentrations of the selected VOCs across study classrooms are relatively low. During the Fall 2001 cooling season with the IDEC systems, only the average indoor minus outdoor concentrations of formaldehyde exceeded 5 ppb, and the concentrations of the majority of the target VOCs were under 1 ppb. This indicates that neither the standard nor the selected alternate materials were substantial compound sources. This agreed with laboratory results of standard and alternate materials conducted prior to the field investigation.

The effects attributable to the use of alternate materials in these classrooms were small and continuous ventilation supplied by the IDEC system had a relatively greater impact on maintaining indoor VOC concentrations at low levels.

## Sound

Teachers volunteered that the IDEC system was quieter than the HPAC system. They all reported that the HPAC system was noisy when the fan was operating.

The RC sound levels were consistent across HVAC system and season, averaging just below 56 dBA. A comparison of occupied and unoccupied periods showed that most of the noise increase above background in the occupied classrooms was due to occupants, with the HPAC and IDEC system operation con-

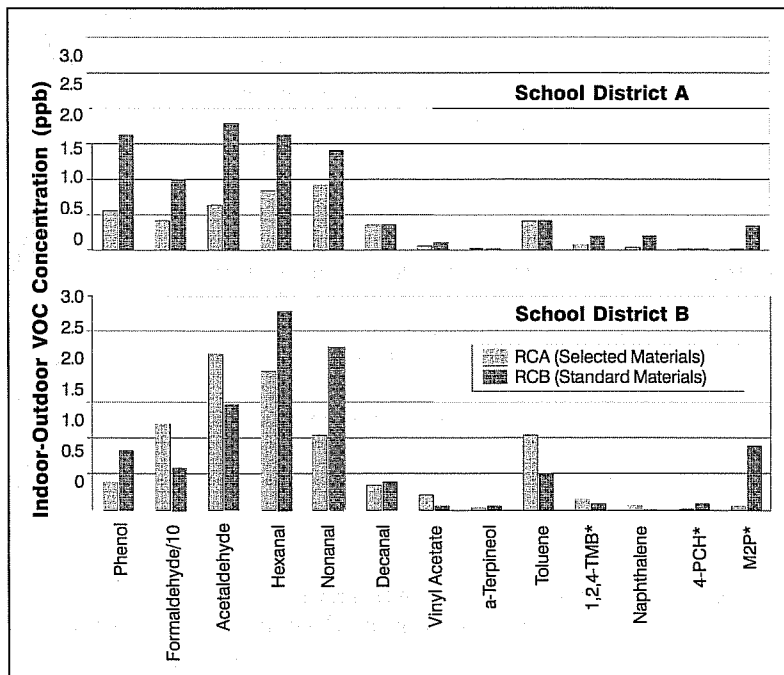


Figure 1. VOC measured in RCs with alternative materials selected vs. those with standard materials. Data represent average indoor minus outdoor VOC concentrations during IDEC operation weeks in the cooling season. Formaldehyde concentrations are divided by a factor of 10. VOCs labeled with asterisks are 1,2,4-trimethylbenzene; 4-phenylcyclohexene; and 1-methyl-2-pyrrolidinone. The selected compounds reflect those that are listed by California as toxic air contaminants or for their odorous characteristics.

tributing up to 14 dBA and 11 dBA, respectively. The data in Table 1 indicate that average RC sound levels were almost the identical (and not statistically different at the 95% confidence level) during operation in both seasons. This does not agree with the teachers' statements that the IDEC operated very quietly. It is possible that a systematic bias in sound level measurements was introduced by the location selected for the sound level monitors in this study.

## Energy Efficiency

Table 1 shows the average energy costs for operating the HVAC during the cooling and heating seasons were lower with the IDEC/hydronic gas heat system than for the HPAC system. On average, cooling costs were halved and heating costs reduced by about a third, while more outside air was concurrently provided for ventilation.

## Conclusions

The goal of this study was to demonstrate the potential to design buildings that can simultaneously use less energy and improve IEQ. The data presented here show clearly that such win-win design implementation could be made in relocatable classrooms, and by inference, in other building types. The differences shown in the comparison between the standard HPAC and the IDEC hybrid are simply a function of improving HVAC energy efficiency and providing adequate and continuous ven-

tilation. The addition of more ventilation could provide similar results, although the potential improvements in energy efficiency of HVAC systems, conventional or otherwise, may provide the greatest savings. Likewise, within limits, designs including indoor pollutant source reduction can potentially reduce ventilation demands.

In this study we were able to show particular reductions in VOC and formaldehyde concentrations by providing a system that assured continuous ventilation. Our efforts in source reduction through careful materials selection did yield somewhat lower VOC concentrations in general, but not to as great an extent as the provision of improved ventilation. Energy savings from the advanced HVAC system were very significant.

The addition of improved outdoor air filtration efficiency on the IDEC system did not appear to provide expected indoor particle concentration reductions, largely due to high indoor particle generation rates in the classroom setting. Teacher reports indicated that noise problems were improved during IDEC system operation weeks, but this was not clearly indicated in the conventional A-weighted sound measurements conducted during occupied periods in the classrooms. This discrepancy warrants further investigation into mitigating acoustic problems in relocatable classrooms.

These overall results suggest that it is possible to use efficient engineering solutions to simultaneously reduce energy consumption and improve indoor environmental quality.

## Acknowledgements

We thank the school districts and manufacturers for their participation. This study was sponsored by the California Energy Commission through the Public Interest Energy Research program as Element 6.2.2 of the Lawrence Berkeley National Laboratory High Performance Commercial Buildings Systems research CEC Contract Number 400-99-012. The study was additionally supported by the U.S. Department of Energy under Lawrence Berkeley National Laboratory contract number DE-AC03-76SF00098.

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## New Chair Begins Term

# Next Steps For SSPC 62.1

*While all will not agree with my assessment of our current position, and with the full understanding of the immensity of the task before us, I will do everything possible as SSPC 62.1 chair to achieve consensus, and to encourage and involve all interested and concerned parties in the process.*

**By David Butler, P.E.,**

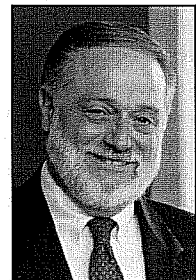
Presidential/Fellow/Life Member ASHRAE

I joined Standing Standards Project Committee 62.1 in 1999 with many preconceived ideas regarding the quality and substance of the standard and the committee as a whole. These ideas were born of years of frustration with applying a standard which, in my opinion as a designer, was sorely lacking. I was convinced by my experience and by comments of other designers that we would never have an IAQ standard of any value to anyone and that "special interests" (whoever that was) had complete control of what was developed.

Fortunately, many of these ideas were ultimately proven to be wrong. The obvious experience, knowledge, and commitment of Standing Standards Project Committee (SSPC) 62.1 members quickly dispelled many of my concerns.

The commitment and the leadership provided by Andy Persily, Ph.D., Member ASHRAE, enabled an almost amazing transformation of the standard during the past four years to a more complete, useful document.

While all will not agree with my assessment of our current position, and with the full understanding of the immensity of the task before us, I will do everything possible as SSPC 62.1 chair to achieve consensus, and to encourage and involve all interested and concerned parties in the process.



**Butler**

## Standard 62 Addenda

Standard 62 Addenda 62g, 62h, 62n, 62x, and 62ae received the Board of Director's approval for publication in July